Simulating Soil Organic Carbon Dynamics with Residue Removal Using the CQESTR Model

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Concerns about CO_2 emissions and fossil fuel supplies have enhanced interest in using crop residues for biofuel production; however, maintaining soil organic C (SOC) through residue return is vital for maintaining soil productivity. Our objectives were to simulate long-term SOC dynamics using CQESTR and to examine the effect of residue harvest on SOC stocks under disking (DT) and conservation tillage (CS). A long-term study in the mid-Coastal Plain region of South Carolina was used to simulate four residue harvest rates (0, 50, 66, and 90%) during two harvest periods. The yearly variation of SOC was predicted well ($r^2 = 0.84$, $P < 0.0001$). Without residue removal, average increases of 0.10 and 0.39 g SOC kg^{-1} yr^{-1} were predicted under DT and CS, respectively, consistent with observed increases of 0.12 and 0.44 g SOC kg^{-1} yr^{-1}. After 23 yr, simulated SOC stock gain was more than threefold greater under CS than DT (9.0 vs. 2.4 g SOC kg^{-1}). The model predicted 1.86 and 4.47 g SOC kg^{-1} losses in the top 5 cm of soil under DT and CS, respectively, during 23 yr of 66% residue harvest compared with no residue harvest. The predicted SOC stocks under CS were ~5 g SOC kg^{-1} greater than under DT, however, even with 90% residue harvest. The quantities of crop residue that can be sustainably harvested were directly influenced by the initial SOC concentration and tillage practices. While CS can somewhat mitigate the loss of soil C, residue harvest from loamy sand soils may have an adverse impact on SOC stocks.

Abbreviations: CS, conservation tillage; DT, disk tillage; NT, no-till; OC, organic carbon; OM, organic matter; SOC, soil organic carbon; SOM, soil organic matter.

Concerns about the impact of CO_2 emissions from fossil fuels on global climate change have prompted interest in sequestering C in soil as SOC to reduce the increase in CO_2 levels in the atmosphere. Carbon sequestration in the soil is one method to mitigate the greenhouse effect and global warming (Follett et al., 2005; Franzluebbers, 2005; Lal, 2005; Lal et al., 1998; Paustian et al., 1995, 1998). Additionally, concerns about declining fossil fuel supplies have renewed the search for lignocellulosic biomass for renewable biofuel energy (Hill et al., 2006; Lynd et al., 1991).

Many types of biomass are available; however, there has been an increasing interest in utilizing agricultural products (grain and crop residues) as feedstock for biofuel production (DiPardo, 2002; Lal, 2007; Perlack et al., 2005). Maize (*Zea mays* L.) grain has been used for industrial ethanol production for more than two decades. Agricultural crop residues comprise the largest near-term source of biomass (Anex et al., 2007). Perlack et al. (2005) estimated that 544 million Mg (dry weight) of biomass could potentially be harvested annually from agricultural land in the United States by 2030, assuming increases in yields (e.g., maize 25%). The largest near-term sources of biomass feedstock are lignocellulosic material from crop residues (e.g., maize and wheat [*Triticum aestivum* L.]). Other sources, including dedicated perennial crops (e.g., switchgrass [*Panicum virgatum* L.]), have been identified (Graham et al., 2007; Sheehan et al., 2003; Tilman et al., 2006). Maize

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Soil Sci. Soc. Am. J. 74:372–383
Published online 8 Jan. 2010
doi:10.2136/sssaj2009.0086
Received 2 Mar. 2009.
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residue (stover), with a current annual availability of approximately 75 Tg (Perlack et al., 2005), is predicted to be the major contributor to biofuel production in the United States, and technologies to convert maize stover to ethanol are under development (Farrell et al., 2006; Kim and Dale, 2005). Consequently, there is growing interest in using maize stover to partially offset energy production from fossil fuel.

Producing biofuel from crop residue is an important potential strategy to reduce the net emission of CO_2 and dependence on fossil fuel (Farrell et al., 2006; Kim and Dale, 2005; Mann et al., 2002; Spatari et al., 2005), yet crop residue is a precious resource essential for the maintenance of soil health, including sequestration of C into soil organic matter (SOM), which reduces atmospheric CO_2 (Lal, 2005, 2007). A considerable amount of research has been conducted addressing the potential environmental impacts and benefits from biofuel production (Farrell et al., 2006; Kim and Dale, 2005; Sheehan et al., 2003); however, little attention has been paid to the soil health consequences associated with crop residue removal for biofuel production (Anex et al., 2007). Harvesting crop residues has been associated with declining soil quality and productivity (Lal, 2005, 2007; Mann et al., 2002; Wilhelm et al., 2007).

Crop production is affected by the interactions of climate, soil properties, and management activities. The interactions among these factors and their effects on yield and soil quality are not always clear, however. Soil organic matter and nutrient dynamics, water availability, erosion, and physical properties within the root zone are strongly affected by the interactions of climate, inherent soil characteristics, and current and past management strategies (i.e., irrigation, tillage type, crop rotations, residue removal, and fertilization). Limited research has shown that removing maize stover reduces grain and stover yield (Power et al., 1986; Wilhelm et al., 1986, 2004) in subsequent crops and decreases SOM levels (Linden et al., 2000; Maskina et al., 1993). Harvesting the majority of crop residue from the current cropping systems would exacerbate the risks of soil erosion (Larson, 1979; Lindstrom, 1986; Lindstrom et al., 1979; Nelson, 2002), increase nonpoint-source pollution, deplete SOM (Maskina et al., 1993; Clapp et al., 2000), degrade soil properties, decrease soil productivity (Wilhelm et al., 1986, 2004), reduce crop yields per unit input of fertilizer and water, and decrease U.S. agricultural sustainability (Lal, 2005, 2007; Mann et al., 2002; Wilhelm et al., 2007). A few studies have examined the effects of residue removal on soil moisture (Swan et al., 1996; Wilhelm et al., 1986, 2004), soil temperature (Sharratt et al., 1998), soil NO_3 leaching and N_2O emissions (Ambus et al., 2001; Aulakh et al., 1991; Gollany et al., 2004; Karlen et al., 1996) and other soil physical, chemical, and biological properties (Blanco-Canqui et al., 2006a,b; Gollany et al., 2004; Karlen et al., 1994; Moebius-Clune et al., 2008).

In some regions, continuous maize production with reduced tillage or no-till (NT) has resulted in a dense ground cover of maize stover. High residue cover provides cool and wet soil conditions that can contribute to weed infestations, fungal disease, herbicide carryover (Locke et al., 2002), and impaired nutrient cycling processes, which can severely reduce plant germination and reduce yield (Kaspar et al., 1990; Siemens and Wilkins, 2006). Under such conditions, residue harvest could improve soil productivity. Elsewhere, however, reduced tillage and NT systems generally accumulate organic C (OC) in the surface soil layers, and increase biological activity, aggregate stability, porosity, and water infiltration (Doran 1980a,b; Liebig et al., 2004; Puget et al., 1999).

In quantifying the effects of residue harvest on soils, most studies have focused on N and SOC dynamics (Clapp et al., 2000; Dolan et al., 2006; Hooker et al., 2005; Lafond et al., 2009; Reicosky et al., 2002; Wilts et al., 2004). Long-term experiments with repeated additions or removals of C sources are ideal for examining SOC changes (Gollany et al., 2006) and have provided insights into SOC dynamics and turnover under a range of agricultural crops and management practices. In a clay soil, Lafond et al. (2009) found no difference in SOC and soil organic N after 50 yr of <40% straw removal in a fallow–spring wheat–spring wheat rotation. Clapp et al. (2000) examined the complex interactions between stover harvest, N fertilization, and SOC dynamics in a 13-yr experiment in Minnesota. They found changes in SOC in both 0- to 15- and 15- to 30-cm depths in response to treatments. Where maize stover was removed from continuous NT maize plots, SOC remained nearly unchanged with time but increased about 14% in plots where stover was returned. Importantly, for C sequestration and long-term soil health, they also found that the half-life for original or relic SOC was lengthened when stover was not harvested and N fertilizer was partially mixed with the stover under a chisel plow system.

Understanding the long-term effects of tillage and crop residue management practices on SOC dynamics and C sequestration is fundamental to sustainable crop residue production for bioenergy. Spatial and temporal aspects of all soil types and management choices, including residue removal, are not fully quantified (Parton et al., 1996; Paul et al., 1997). The crop production potential of a soil is related strongly to its organic matter (OM) content (Gollany et al., 1992; Lal et al., 1998; Mann et al., 2002), which in part is controlled by OC inputs such as crop residue or organic amendments. The amount of SOC in an agricultural soil is the net difference between inputs of organic matter and outputs through mineralization, loss and deposition by erosion, and translocation of dissolved OC through the soil profile (Campbell et al., 1996; Mertens et al., 2007). Soil C in its stable form as SOM responds gradually to agricultural management changes. Because of this slow process and the complex interactions between climate, edaphic, and management factors, simulation models (Huggins et al., 1998; Izaurralde et al., 2006; Liang et al., 2008; Paustian et al., 1992; Rickman et al., 2002) have been used to describe and predict the short- and long-term effects of management practices on SOC dynamics and turnover.

While there are several recent reports discussing the consequences of maize stover harvest for biofuel production, most research on maize stover harvest has been conducted in the central

U.S. Corn Belt. A long-term study in the mid-Coastal Plain region of South Carolina was selected for its documented history of tillage and management, including past records of short-term residue removal, and periodic SOC measurements (Karlen et al., 1984). Our objectives were to: (i) simulate long-term changes in SOC dynamics for an agricultural site in the southeastern United States using the CQESTR model; and (ii) examine the effect of tillage and residue harvest on SOC contents while utilizing four crop residue removal or harvest scenarios for bioenergy production.

MATERIALS AND METHODS

Site Description and Management Practices

A long-term tillage and crop management study was initiated in 1979 at the Clemson University Pee Dee Research and Education Center near Florence, SC (34°18' N, 79°44' W). The study was conducted on a 2.65-ha tract of Norfolk loamy sand (a fine-loamy, kaolinitic, thermic Typic Kandiudult) that is typical of the mid-Coastal Plain region of South Carolina. The soil is well drained and the plow layer (0–20 cm) contains about 787 g kg^{-1} sand, 185 g kg^{-1} silt, and 28 g kg^{-1} clay (Karlen et al., 1996). The site has a uniform slope of <1%. The mean annual precipitation at the Pee Dee Research and Education Center during the past 22 yr is 1109 mm, and the average air temperatures in January and July are 7.1 and 26.8°C, respectively (Karlen et al., 1996). The number of growing degree days (base 10°C) range from 348 (during winter wheat growth) to 1086°C (Hunt et al., 2004). Before 1979, the site was farmed using mechanical cultivation and DT under a maize and soybean [*Glycine max* (L.) Merr.] rotation. When this study commenced, 20 plots of 0.15 ha (60- by 23-m) size were established to compare tillage (conventional [DT, disking to the 15-cm depth and paratilling to 40-cm depth] vs. conservation [CS, paratilling to 40-cm depth]) and irrigation effects on maize yields (Karlen et al., 1984), with 10 replications. The irrigation experiment was discontinued after 1982, and a 2-yr, three-crop rotation experiment was established in these plots (Table 1).

In all plots, some form of tillage operation was performed annually. Both tillage treatments received in-row subsoiling (paratilling) at planting to fracture a root-restrictive layer (E horizon) that recements in the Norfolk soil (Busscher et al., 1986). In plots under DT, the soil bed was prepared by one-pass disking to a depth of 15 cm followed by smoothing using an S-tined harrow equipped with a rolling basket (Table 1). Under DT, surface disruption resulted from cultivation to control weeds and incorporate crop residue, fertilizer, and lime. Conservation tillage eliminated the surface tillage. Plots under CS were only in-row subsoiled and planted using a one-pass operation. Initially, a one-pass subsoiling and planting operation was performed with a Brown-Harden superseeder (Brown Manufacturing Corp., Ozark, AL). Later this equipment was replaced with a Kelly Manufacturing Co. (Tifton, GA) in-row subsoiler and a Case IH Model 800 planter (Case-IH, Racine, WI). Between 1996 and 2003, the in-row subsoiling operation was replaced with a paratilling to 40-cm depth using a Tye ParaTill (AGCO Corp., Duluth, GA), with shanks spaced 66 cm apart.

Each plot was double cropped with maize followed by winter wheat followed either by cotton (*Gossypium hirsutum* L.) or soybean (Hunt et al., 1996). In the first year of this rotation, 10 plots (five plots under CS and five under DT) were planted with maize during one season, while the remaining 10 plots were doubled cropped with wheat followed by cotton or soybean. In the second year, the plots that were previously in maize were double cropped with wheat followed by soybean. Maize was planted on the remaining plots. Maize and cotton were grown in rows spaced either 20 or 76 cm, whereas wheat and soybean were planted in 20-cm rows. The plots were left fallow because of poor seed germination during the drought in 1987 (Table 1). Soil fertility and weed control programs used were typical for these crops in the mid-Coastal Plain region (Hunt et al., 2004).

Crop yields were obtained from all plots; however, the time and area of harvest varied with the crop. Cotton was harvested from 59 m^2 of the row with a two-row spindle picker in October (Hunt et al., 1997). Maize was harvested from 547 m^2 (12 60-m rows) within each plot with a Case IH Model 2366 combine in August or September. In June, wheat was harvested from 540 m^2 (9 by 60 m) of each plot using the same combine. Soybean was harvested from a similar size area as wheat, with plant residue samples collected during October to December. Details of the maize, wheat, and soybean planting and harvesting were given by Karlen et al. (1996) and Hunt et al. (2004).

Shoot Dry Matter and Crop Residue Collection

Total shoot dry matter estimates were obtained using methods described by Hunt et al. (1997, 2004). For maize, this was accomplished by randomly selecting six plants and collecting shoot samples from three locations within each plot in July. Wheat and soybean shoot dry matter samples were collected from three locations (1 m^2) within each plot in April to May and September to October, respectively. Cotton shoot dry matter was estimated by collecting samples from a 0.76-m^2 area at three locations within each plot.

Estimates of aboveground plant residue densities from each crop were obtained within 1 to 2 wk after harvest by collecting debris at three locations within each plot, using a 0.25- or 1-m^2 grid. Samples from the three locations were composited, dried between 60 and 70°C, and weighed. Plant residue samples were then ground for OC analysis.

Soil Sampling and Organic Carbon Measurements

Soil cores were collected after maize harvest from three locations within each of the five plots per tillage treatment. Soil samples were collected annually except in 1984, 1985, 1987, 1993, and 1999. The depth

Table 1. Crop rotations and tillage management practices used on the long-term plots at the Clemson University Pee Dee Research and Education Center near Florence, SC, from 1979 to 2003.

Time period	Crop rotation†	Tillage practice: Conservation	Tillage practice: Disk
1979–1982	M	in-row subsoil	disk, in-row subsoil
1983–1986	M–WW–SO	in-row subsoil	disk, in-row subsoil
1987	F	in-row subsoil	disk, in-row subsoil
1988	M	in-row subsoil	disk, in-row subsoil
1989–1996	M–WW–CO	in-row subsoil	disk, in-row subsoil
1996–2003	M–WW–SO	paratill	disk, paratill

† M, Maize; CO, cotton; F, fallow; SO, soybean; WW, winter wheat.

of sampling varied with the time of the study. In 1979, soil cores were obtained only from the 0- to 5-cm soil depth using a soil probe. From 1980 through 1986, soil cores were collected with a soil probe from the 0- to 5-, 5- to 10-, and 10- to 15-cm depths. After 1988, soils cores were obtained from the 0- to 5-, 5- to 10-, 10- to 15-, 15- to 30-, 30- to 45-, 45- to 60-, and 60- to 90-cm depths, using a Giddings auger probe (Giddings Machine Co., Windsor, CO). All soil cores within a treatment plot were composited by depth. Crop residues were removed from the soil surface before samples were taken. All samples were air dried, crushed, and passed through a 2-mm-mesh sieve to remove plant debris.

Soil and crop residue samples were analyzed for OC using three different instruments (Hunt et al., 1996). In 1979, the dry combustion method of Nelson and Sommers (1982) was used. From 1980 through 1987, a LECO C analyzer (Model CN200, LECO Corp., St. Joseph, MI) and a Carlo-Erba (Milan, Italy) analyzer (1988–1992) were used to determine OC in the samples. After 1993, all soil and plant samples were analyzed using the LECO C analyzer. The Norfolk loamy sand is an acidic soil with soil profile pH values <6.0; therefore, the total C pool was assumed to be OC (Novak et al., 2007).

Model Description

The CQESTR model is a process-based model in which each organic residue addition is tracked separately, without partitioning, according to its placement within distinct soil horizons (Liang et al., 2008, 2009; Rickman et al., 2002). The CQESTR model was developed to evaluate the effect of management practices on short- and long-term trends of SOM (Rickman et al., 2001) using readily available input data at the field scale. It operates on a daily time step and can perform long-term (100-yr) simulations (Liang et al., 2009; Rickman et al., 2001). The major input variables are: (i) the mean monthly total precipitation and air temperature, (ii) the depth and number of soil horizons, (iii) the initial SOM content and bulk density of each horizon, (iv) tillage information, (v) crop rotation and annual yields, (vi) the root distribution characteristics of the crops, (vii) organic amendments (i.e., manure), and (viii) the N content of both the crop residues and organic amendments. Crop rotation and tillage information are required explicitly for the layer-by-layer computation performed by the model. Crop rotation, annual yields, and tillage information were organized in crop management files associated with the *C* factor of the Revised Universal Soil Loss Equation (RUSLE, Version 1) (Renard et al., 1996). The RUSLE *C*-factor files, used as input files for CQESTR, consist of crop grain yields, shoot/grain ratios, dates of all operations (e.g., tillage, seeding, harvest, biomass addition, biomass removal, etc.), and the effects of tillage on residue (e.g., the fraction of pretillage residue weight remaining on the soil surface after each tillage, the depth of tillage, and the fraction of the surface disturbed by each operation).

Model Simulation Scenarios

In this study, CQESTR was used to simulate SOC dynamics in a long-term experiment with crop rotations under two tillage practices—disking or paratilling, with both receiving in-row subsoiling—and simulated results were compared with measured values. Two residue removal periods considered in the CQESTR simulations were: Period 1 (P1), where crop residues were harvested from the plots from 1979 to 2002; and Period 2 (P2), where crop residues were harvested from the plots from 1995 through 2014 (Table 2). Four crop residue (maize and wheat) removal or harvest scenarios were simulated representing different amounts of crop residue harvest for biofuel production. The residue harvest scenarios were denoted H0, H50, H66, and H90, representing conditions where 0, 50, 66, and 90%, respectively, of the crop aboveground biomass (other than grain and the root crown) was harvested. The 66 and 90% removal conditions were selected to estimate the effect of the past crop residue removal experiment conducted on the site for 4 yr (1979–1982), where N, P, and K were measured but SOC was not determined (Karlen et al., 1984). Crop residues were harvested by varying the cutting height of a flail-type forage harvester (Karlen et al., 1984). In P1, the H0, H66, and H90 harvest scenarios were simulated for the CS treatment to examine the SOC status after 23 yr of residue removal. In P2, the H0, H50, and H90 harvest scenarios were simulated to follow the proposed USDA-ARS Renewable Energy Assessment Project (REAP) residue harvest scenarios, and to predict the SOC status following changes in management practices after increased SOC levels. Without residue harvest, the actual SOC increased by about 0.5 and 1.5% for DT and CS, respectively, by 1995. The H0 scenario represents the baseline (i.e., initial and current SOC level), a condition where all of the maize stover and wheat straw is left in the field and only grain is removed from the plots. Simulation responses from residue harvest were compared with the baseline scenarios (H0).

Actual annual grain and residue yields between 1997 and 2002 were used in the P2 simulation (assuming comparable yields throughout the period of simulation), with the resulting harvest of maize stover and wheat straw under both tillage treatments being equivalent to each harvest rate. The simulation of the 50% harvest rate (H50) assumed that 2.4 to 3.8 Mg ha^{-1} of maize stover and 1.3 to 2.2 Mg ha^{-1} of wheat straw was removed. In the H66 scenario, a range of 2.7 to 5.4 Mg ha^{-1} for maize stover yield and a range of 2.2 to 3.0 Mg ha^{-1} for wheat straw yield were used. In the simulation of CS with the H90 harvest scenario, 4.0 to 7.3 Mg ha^{-1} of maize stover and 3.1 to 4.1 Mg ha^{-1} of winter wheat straw were used. No residue removal was considered for the soybean, rye (*Secale cereal* L.), or cotton crops.

Since the original residue harvest experiment was implemented only on the CS plots, we imposed only a 66% residue harvest on the DT treatment during the P1 scenarios to illustrate the possible impact of residue removal on this soil with low inherited SOC. Furthermore, scenarios were simulated to examine a key policy-relevant

Table 2. Residue harvest periods and harvest rate scenarios† used for the disk and conservation tillage treatments.

Treatment	Period 1 (1979–2002)			Period 2 (1995–2014)		
	H0	H66	H90	H0	H50	H90
Disk tillage (DT)	yes	yes	no	yes	yes	yes
Conservation tillage (CS)	yes	yes	yes	yes	yes	yes
Conversion from DT to CS (1995)	no	no	no	yes	yes	yes

† H0, no residue was harvested; H50, H66, and H90 where 50, 66, and 90% of aboveground biomass other than grain and the root crown being harvested.

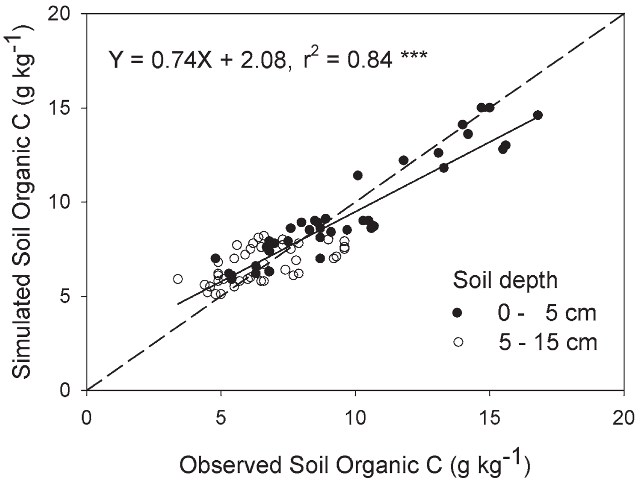

Fig. 1. Comparison of simulated and observed soil organic C in the 0- to 5-, and 5- to 15-cm soil depths for disk tillage and conservation tillage at Florence, SC. ***Significant at the 0.001 probability level.

question about the potential of residue harvest impact mitigation by utilizing less intensive tillage practice (i.e., CS). Simulation was conducted by imposing conversion from DT to CS in 1995, when the observed SOC content had reached a new plateau, semiequilibrium condition (Novak et al., 2007). Two residue harvest rates were simulated, H50 and H90, with three assumptions made for these scenarios: (i) actual yields from CS between 1997 and 2002 were assumed to be common yields at this location if no removal occurred; (ii) the yields of H50 in the first 6 yr immediately after conversion from 16-yr DT plots were assumed to be 80% of the actual CS yields, because of reduced N availability under reduced tillage due to N immobilization (Andraski and Bundy, 2008) and lower mineralization rates under CS (Bauer et al., 2006); and (iii) the yields of H90 in all years after conversion from 16-yr DT plots were assumed to be 70% of the actual CS yields, for similar reasons as stated above but with more severe consequences due to the higher rate of residue harvest.

Statistical Procedures

Linear regression (PROC REG) and Pearson correlation (PROC CORR) procedures were used to estimate the parameters and their statistical significance (SAS Institute, 2003). Analysis of variance was used to compute a standard error of the mean. Mean square deviation (MSD) statistics were also used to evaluate the predictive performance of the model against measured data. According to Gauch et al. (2003), the MSD is partitioned into three components: nonunity slope (NU), lack of correlation (LC) or scatter, and squared bias (SB). All three components relate to terms of the linear regression equation ($Y = a + bX$) and the regression coefficient (r^2).

In a set of observed (X) and simulated values (Y), the MSD is defined as MSD = $\Sigma(X_n - Y_n)^2/N$ for $n = 1, 2, ..., N$. The first component of MSD, nonunity (NU), measures the degree of rotation of the regression line and is defined as NU = $(1 - b)^2\Sigma x_n^2/N$, where b is the slope of the least-square regression of Y on X, $b = \Sigma x_n y_n/\Sigma x_n^2$, $x_n = X_n - \overline{X}$, and $y_n = Y_n - \overline{Y}$. The second component, lack of correlation or scatter (LC), is calculated as LC = $(1 - r^2)\Sigma y_n^2/N$, where r^2 is the coefficient of determination $(\Sigma x_n y_n)^2/(\Sigma x_n^2 \Sigma y_n^2)$. The third component, SB = $(\overline{X} - \overline{Y})^2$, gives a measure of the inequality between the two means $\overline{X}$ and $\overline{Y}$ (Gauch et al., 2003).

Table 3. Residual difference between observed and estimated soil organic C stocks (expressed as a percentage of observed) under disk tillage (DT) and conservation tillage (CS) in 2002.

Tillage	Soil depth	Soil organic C		
		Observed	Estimated	Residual
	cm	g kg^{-1}		%
DT	0–5	10.3	9.0	12.6
	5–10	9.0	8.0	11.0
	10–15	6.4	6.3	1.6
CS	0–5	15.3	14.9	2.6
	5–10	10.1	8.2	18.8
	10–15	6.3	7.6	20.6

RESULTS

Performance of the CQESTR Model

Observed vs. simulated SOC values, without residue harvest (H0), for the three soil depths of the DT and CS treatments were used to evaluate the CQESTR model performance (Fig. 1; Table 3). Regression analysis of 81 pairs of simulated and observed values were closely related ($r^2 = 0.84$), with a slope not significantly ($P < 0.0001$) different from 1. This was also supported by a high Pearson correlation coefficient ($r = 0.92$) and small MSD (1.50). The contributing components of the MSD were in the following order: scatter (LC = 1.3996 or 92% of MSD) > rotation (NU = 0.1071 or 7%) > translation (SB = 0.0001). Furthermore, the predictive performance of CQESTR is illustrated by the small calculated residuals for each soil depth in 2002 (Table 3).

Soil Organic Carbon Dynamics of Conventional Tillage

The simulated and measured temporal changes in SOC for the 0- to 5-, 5- to 10-, and 10- to 15-cm soil depths under DT are illustrated in Fig. 2. The mean and standard error of the measured SOC stocks in the 0- to 5-cm depth for DT were 6.3 ± 0.8 g SOC kg^{-1} in 1979 (Novak et al., 2007). The CQESTR model captured the temporal change in SOC stocks well for the 0- to 5-cm soil depth. An increase of 2.4 g SOC kg^{-1} in the 0- to

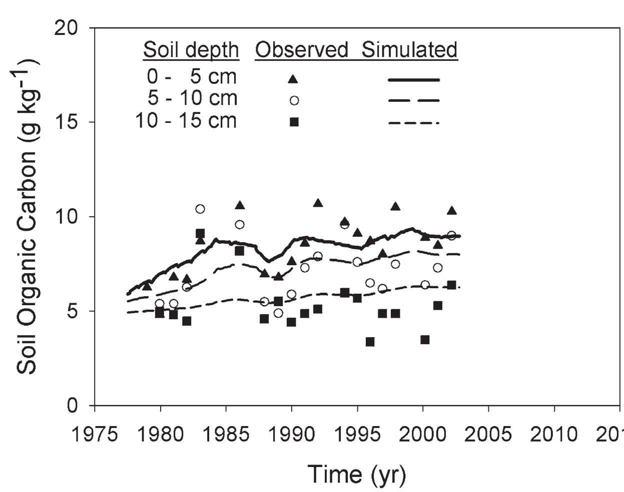

Fig. 2. Simulated and observed soil organic C dynamics in the 0- to 5-, 5- to 10-, and 10- to 15-cm soil depths without residue harvest for disk tillage at Florence, SC. The symbols are measured values and the lines are simulations from the CQESTR model.

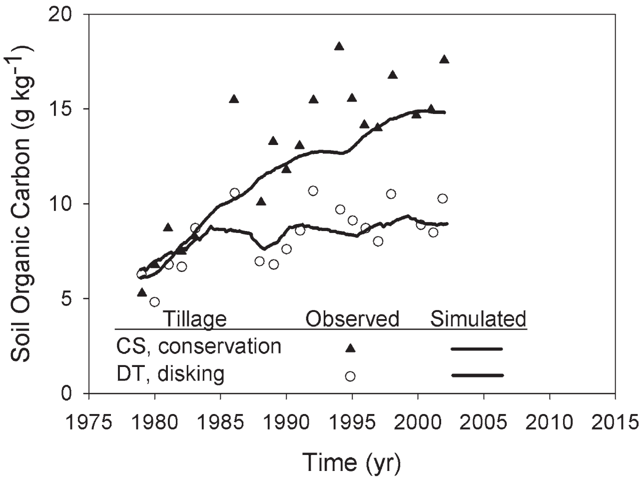

Fig. 3. Simulated and observed soil organic C dynamics in the 0- to 5-cm soil depth without residue harvest for disk tillage (DT) and conservation tillage (CS). The symbols are measured values and the lines are simulations from the CQESTR model.

5-cm depth was observed from 1979 to 1983. The model also predicted an increase in SOC stocks from 6.5 to 8.5 g SOC kg^{-1} in the 0- to 5-cm depth during the same 4-yr period. The observed SOC values decreased in the late 1980s because of management changes after 1986, and this was also simulated by CQESTR. Another increase in SOC occurred when paratilling was substituted for in-row subsoiling after 1996. Temporal changes in SOC for the 5- to 10- and 10- to 15-cm soil depths followed the same pattern as for the 0- to 5-cm soil depth (Fig. 2).

Soil Organic Carbon Dynamics of Conservation Tillage

The observed SOC values increased from 5.3 to 13.3 g SOC kg^{-1} in the 0- to 5-cm depth for the CS treatment during the first 10 yr (Fig. 3). The mean and standard error of the measured SOC content in the 0- to 5-cm depth for CS were 5.3 ± 0.2 g SOC kg^{-1} in 1979. The simulated SOC values followed the same trend as the measured values. The CQESTR model predicted an increase in SOC values from 6.01 to 12.76 g SOC kg^{-1} in the 0- to 5-cm depth during the first 10 yr. The simulated SOC stocks for the CS system increased from 6.01 to 14.9 g SOC kg^{-1}, while the observed values increased from 5.3 to 15.3 g SOC kg^{-1} during 23 yr. The model tended to underestimate some high SOC values for the CS system in the late 1990s. The residuals for all three soil depths of the CS system are relatively small, <1.9 g SOC kg^{-1} (Table 3). Temporal changes in SOC for the 5- to 10- and 10- to 15-cm soil depths followed the same pattern as for the 0- to 5-cm soil depth (data not shown).

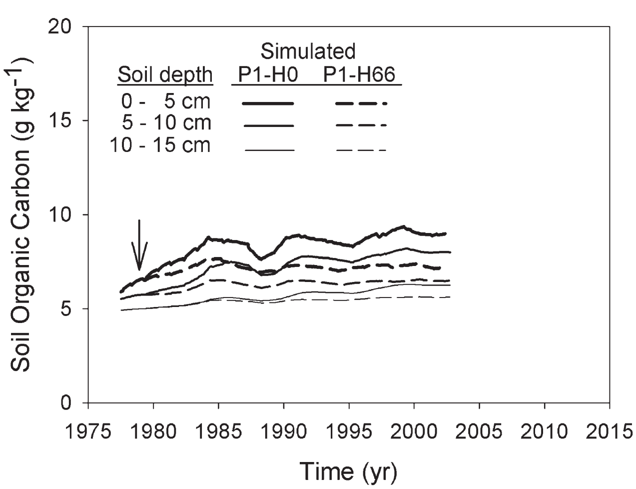

Fig. 4. Simulated soil organic C dynamics in the 0- to 5-, 5- to 10-, and 10- to 15-cm soil depths for disk tillage under 0% (H0) or 66% (H66) residue harvest scenarios of Period 1 (P1, 1979–2002). The vertical arrow indicates establishment of residue harvest simulation, which was initiated in 1979.

Tillage Effect on Soil Organic Carbon Stocks

Rates of C sequestration were noticeably different under the two tillage systems, with essentially the same residue inputs (H0) in the 0- to 5-cm soil depth for 23 yr (Fig. 3). The SOC stocks doubled in the 0- to 5-cm depth after 14 yr of continuous use of the CS system. After 23 yr of cropping, CQESTR predicted an increase of 9.0 g SOC kg^{-1} in the 0- to 5-cm soil depth under CS, which is more than three times greater than the 2.4 g SOC kg^{-1} for DT (Fig. 2, and 3). This is equivalent to a yearly increase of 0.10 and 0.39 g SOC kg^{-1} for the DT and CS systems, respectively.

Potential Effects of Residue Harvest on Soil Organic Carbon Stocks in Disk Tillage System

The potential effects of residue harvest on SOC stocks in the DT system at the three soil depths (0–5, 5–10, and 10–15 cm) were simulated under the P1-H0 and P1-H66 scenarios (Fig. 4). The model predicted losses of SOC in all three soil depths following 23 yr of 66% residue harvest (Table 4). A decrease in SOC from 9.0 to 7.1 g SOC kg^{-1} in the top 5-cm soil depth under the DT system was predicted by CQESTR. The predicted decreases in SOC stocks were 1.5 and 0.8 g SOC kg^{-1} for the 5- to 10- and 10- to 15-cm soil depths, respectively.

The effects of three residue harvest rates under the proposed REAP scenarios (P2-H0, P2-H50, and P2-H90) on SOC stocks in the DT system were also examined at three soil depths (0–5, 5–10, and 10–15 cm) (Fig. 5). A 50% residue harvest from 1995 to 2014 resulted in 0.7 and 0.6 g SOC kg^{-1} losses in simulated SOC values in the 0- to 5- and 5- to 10-cm depths, respectively (Table 4). The 90% residue harvest for 19 yr decreased SOC by 1.0 and 0.8 g SOC kg^{-1} in the 0- to 5- and 5- to 10-cm depths, respectively, compared with the H0 scenario.

Table 4. Simulated soil organic C (SOC) stocks under disk tillage at three depths, with four residue harvests (H0, H50, H66, and H90†) during two periods (1979–2002 and 1995–2014).

Soil depth	1979–2002		1995–2014		
	P1-H0	P1-H66	P2-H0	P2-H50	P2-H90
cm	g SOC kg^{-1}				
0–5	9.0	7.1	9.2	8.5	8.2
5–10	8.0	6.5	8.2	7.6	7.4
10–15	6.4	5.6	6.6	6.5	6.5

† H0 = no residue was harvested; H50, H66, and H90 = 50, 66, and 90%, respectively, of aboveground biomass other than grain and the root crown were harvested.

Potential Conservation Tillage Mitigation of Residue Harvest Impact on Soil Organic Carbon Stocks

Simulation of a 50% residue harvest (H50) resulted in decreased SOC stocks in the 0- to 5-cm depth by 0.6 g SOC kg^{-1} in the first 3 yr after changing management from DT to CS, a less intensive tillage practice (Fig. 6b). Simulated SOC stocks decreased by 0.5 g SOC kg^{-1} in the 5- to 10-cm depth from 1996 to 2003, then started to increase after 2004. During the 19 yr of CS tillage with 50% residue harvest, SOC stocks increased from 9.3 to 12.3 g SOC kg^{-1} in the 0- to 5-cm depth and from 6.2 to 7.5 g SOC kg^{-1} in the 10- to 15-cm depth after conversion from DT. After 19 yr of 90% residue removal (H90) and conversion to less intensive tillage (i.e., CS), the simulated SOC stocks decreased only in the 5- to 10-cm depth, while SOC stocks were maintained in the 0- to 5- and 10- to 15-cm depths (Fig. 6c). The predicted SOC stocks declined by 0.7 g SOC kg^{-1}, from 8.1 to 7.4 g SOC kg^{-1}, in the 5- to 10-cm soil depth under CS with 90% residue harvest.

Potential Effects of Residue Harvest on Soil Organic Carbon Stocks in Conservation Tillage System

The simulated residue harvest effect on SOC stocks in the CS system was examined at two soil depths (0–5 and 5–10 cm) under three residue harvest rates scenarios (P1-H0, P1-H66, and P1-H90) (Fig. 7). After 23 yr of 66% residue harvest, CQESTR predicted a decrease in SOC stocks from 14.9 to 10.4 g SOC kg^{-1} in the top 5-cm soil depth (Table 5). The predicted SOC stock decline in the 5- to 10-cm soil depth under the P1-H66 residue harvest scenario was from 8.2 to 6.7 g SOC kg^{-1}. Following 90% residue harvest, CQESTR predicted decreases in SOC stocks by 6.1 and 2.3 g SOC kg^{-1} at the 0- to 5- and 5- to 10-cm depths, respectively.

The effects of three residue harvest rates (P2-H0, P2-H50, and P2-H90) were simulated at two soil depths (0–5 and 5–10 cm) under the P2 scenario (Fig. 8). After 50% biomass harvest from 1995 to 2014, CQESTR predicted declines of SOC stocks from 17.2 to 15.8 g SOC kg^{-1} for the 0- to 5-cm depth and from 9.7 to 9.2 g SOC kg^{-1} for the 5- to 10-cm soil depth (Table 5). Residue harvests for 19 yr under the P2-H90 scenario decreased SOC stocks in the 0- to 5- and 5- to 10-cm soil depths by 4.0 and 1.1 g SOC kg^{-1}, respectively.

DISCUSSION

Model Performance

Generally, CQESTR performed well in estimating the SOC dynamics in spite of some high observed values. Simulated and measured SOC values in the 0- to 5-cm depth had a strong linear relationship (r^2 = 0.87, n = 36, data not shown). The simulated SOC stocks in the 0- to 5-cm depth under the CS system after 23 yr was 14.9 g SOC kg^{-1}, whereas the mean measured value in 2003 was 15.3 g SOC kg^{-1}. The CQESTR model underestimated SOC stocks for CS by 0.4 and 1.9 g SOC kg^{-1} in the 0- to 5- and 5- to 10-cm soil depths,

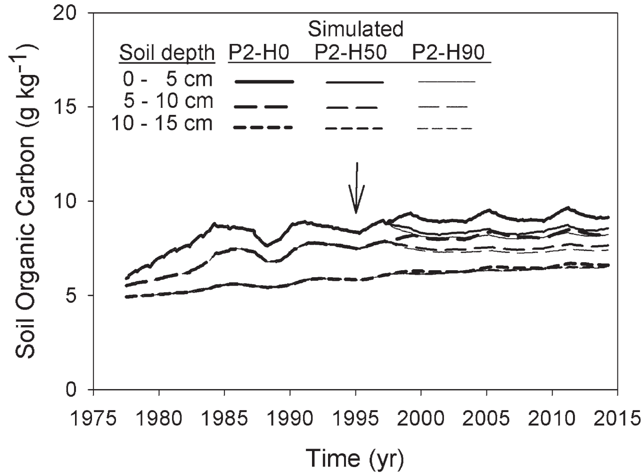

Fig. 5. Simulated soil organic C dynamics in the 0- to 5-, 5- to 10-, and 10- to 15-cm soil depths for disk tillage under 0% (H0), 50% (H50), or 90% (H90) residue harvest scenarios of Period 2 (P2, 1995–2014). The vertical arrow indicates establishment of residue harvest simulation, which was initiated in 1995.

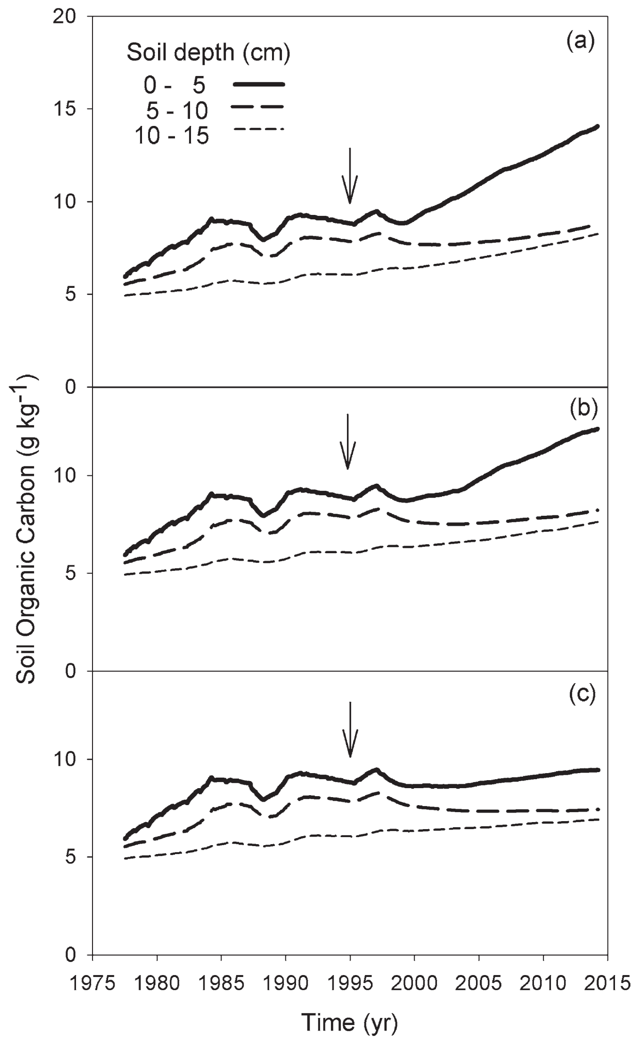

Fig. 6. Simulated soil organic C dynamics in the 0- to 5-, 5- to 10-, and 10- to 15-cm soil depths for disk tillage under (a) 0%, (b) 50%, or (c) 90% residue harvest scenarios of Period 2 (1995–2014) and management change to conservation tillage in 1995. The vertical arrow indicates establishment of residue harvest simulation, which was initiated in 1995.

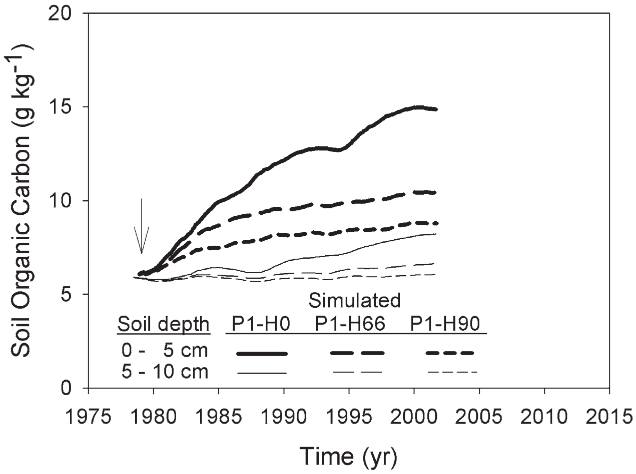

Fig. 7. Simulated soil organic C dynamics in the 0- to 5- and 5- to 10-cm soil depths for conservation tillage under 0% (H0), 66% (H66), or 90% (H90) residue harvest scenarios of Period 1 (P1, 1979–2002). The vertical arrow indicates establishment of residue harvest simulation, which was initiated in 1979.

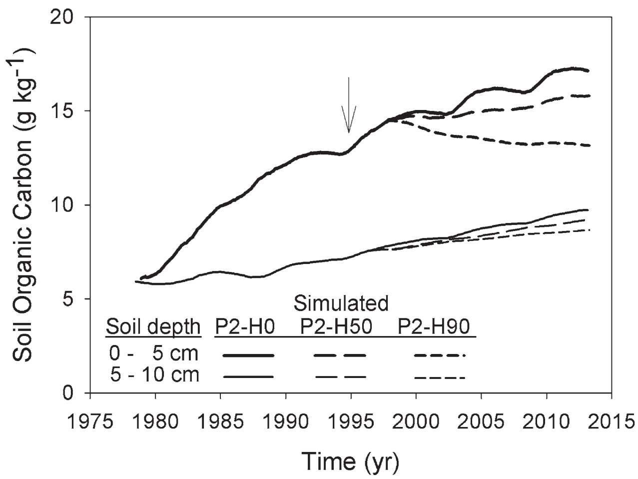

Fig. 8. Simulated soil organic C dynamics in the 0- to 5- and 5- to 10-cm soil depths for conservation tillage under 0% (H0), 50% (H50), or 90% (H90) residue harvest scenarios of Period 2 (P2, 1995–2014). The vertical arrow indicates establishment of residue harvest simulation, which was initiated in 1995.

respectively (Table 3). These small underestimated values would be acceptable considering the annual variations in mean measured SOC values of about 15% (Fig. 2 and 3). The model overestimated SOC stocks by only 1.3 g SOC kg^{-1} (20.6%) in the 10- to 15-cm depth for the CS treatment.

Soil Organic Carbon Dynamics of Conventional Tillage

An increase of 0.6 g SOC kg^{-1} yr^{-1} measured in the 0- to 5-cm depth (Fig. 2) during the first 4-yr period was probably due to high yields and associated residue returned as a result of improved management practices (e.g., irrigation). Karlen et al. (1984) reported that the use of rye as a cover crop and irrigation in these plots had increased the yield and residue return from 1979 to 1980. Simulated SOC stocks followed the same trend as the observed SOC values (Fig. 2). The CQESTR model predicted an increase of 0.5 g SOC kg^{-1} yr^{-1} in the 0- to 5-cm depth during the same 4-yr period. The model results generally indicated that winter cover crops can increase SOC levels, especially in the southern and southeastern United States (Mann et al., 2002). The observed SOC values decreased in the late 1980s because of crop failure and a fallow rotation under drought conditions in 1987, and this was also simulated by CQESTR. Karlen et al. (1989) reported an increase of 6.9 g SOC kg^{-1} in the 0- to 5-cm soil depth of the same plots after 8 yr, presumably because of intensive crop management and good crop yields.

Table 5. Simulated soil organic C (SOC) stocks under conservation tillage at two depths, with four residue harvests (H0, H50, H66, and H90†) during two periods (1979–2002 and 1995–2014).

Soil depth	1979–2002			1995–2014		
	P1-H0	P1-H66	P1-H90	P2-H0	P2-H50	P2-H90
cm	g SOC kg^{-1}					
0–5	14.9	10.4	8.8	17.2	15.8	13.2
5–10	8.2	6.7	5.9	9.7	9.2	8.6

† H0 = no residue was harvested; H50, H66, and H90 = 50, 66, and 90%, respectively, of aboveground biomass other than grain and the root crown were harvested.

The predicted and observed SOC values increased by about 2.9 g SOC kg^{-1}, on average, in the top layer during the 23 yr since the initiation of the experiment, perhaps because of intensifying crop rotations, reduced tillage operations, and double cropping. Novak et al. (2007) concluded that the SOC content in the 0- to 5-cm soil depth under DT was near steady-state equilibrium and the SOC stock had reached a plateau at about the 14th yr of the study (approximately 1993). The constant trend in observed SOC stocks and the slight upward trend in the simulated SOC values suggest that a significant increase in SOC cannot be expected unless a change in management occurs.

Tillage Effect on Soil Organic Carbon Stocks

A pronounced increase in SOC stocks under CS compared with DT was observed, especially from 1979 to 1992 (Fig. 3). Novak et al. (2007) attributed lower C sequestration rates under DT than under CS to higher oxidation and decomposition rates because of residue incorporation into the soil. The CQESTR model predicted an increase in SOC stocks under CS of 6.7 g SOC kg^{-1}, while the observed SOC values increased by 8.0 g SOC kg^{-1} in the 0- to 5-cm depth during the first 10 yr. Significant SOC changes were limited to the 0- to 5-cm depth, as reported by Novak et al. (2007). This increase was predicted by CQESTR as well and was probably due to the reduction in surface tillage except for subsoiling. Bono et al. (2008) suggested a lower OM mineralization rate as a mechanism for C accretion under a CS system. Furthermore, Bauer et al. (2006) showed that CO_2 efflux at this site was slower under CS than under DT due to the accumulation of residue at the soil surface and a lower crop residue oxidation rate.

The rates of C sequestration were noticeably different under the two tillage systems with essentially the same residue inputs. The total amount of OM produced and added to the soil depends on climatic conditions, soil water status, soil properties, nutrient availability, the growth and allocation to roots, stalks, and grain, management activities (i.e., irrigation, tillage type and frequency, fertilization, rotations, and cropping intensity), and the residue harvest rate. As annual biomass inputs increase, SOC usually increases until a new equilibrium is reached, at which point the C flux remains constant. The rate of soil C change is directly related to C input from crop residues (Rasmussen and Parton, 1994). Both the DT and CS treatments were under a double-cropping system, in which the amount of residue returned to the soil was essentially the same (Hunt et al., 2004). The decomposition rate was enhanced under DT, however, due to disking activities. Hunt et al. (1996) reported that SOC stocks doubled in the 0- to 5-cm depth of this soil after 14 yr of continuous use of a CS system. Similarly, conversion to NT from tilled practices (especially plowed systems) has been shown to improve the SOC content in the topsoil across diverse soils (West and Post, 2002). This increase in SOC stocks could improve soil properties including soil structure, aeration, water retention, biological activity, and nutrient cycling (Powlson et al., 2008).

Potential Effects of Residue Harvest on Soil Organic Carbon Stocks under Disk Tillage

The CQESTR model predicted losses of SOC in the DT system at all three soil depths under P1-H66 compared with the H0 scenario (Fig. 4, and Table 4). The model predicted a decrease of 21% in the top 5-cm soil depth under the DT system. The predicted decrease in SOC stocks were 19 and 12% for the 5- to 10- and 10- to 15-cm soil depths, respectively. The predicted decrease in SOC for the 10- to 15-cm soil depth was noticeable after 5 yr of simulated residue harvest, while the top two depths showed a decline in SOC after 1 yr. Crop residue removal may reduce SOC stocks unless the cropping system can maintain a net positive or neutral C balance after residue removal (Anex et al., 2007). Reducing the tillage intensity, altering crop rotations, introducing cover crops (e.g., ryegrass [*Lolium multiflorum* Lam.]) may reverse SOC stocks decline.

A 50% residue harvest rate under the P2-H50 scenario resulted in 8 and 7% losses in simulated SOC in the 0- to 5- and 5- to 10-cm depths, respectively (Fig. 5; Table 4). The 90% residue harvest for 19 yr under the P2-H90 scenario decreased SOC stocks by 11% in the 0- to 5-cm depth and by 10% in the 5- to 10-cm depth. Residue harvest impact during the P2 scenarios may have been influenced by the initial SOC stocks of the soil. The SOC stocks in 1995, when the P2 residue harvest was implemented, were about 0.5% higher than in 1979. Several studies have shown that residue harvest not only depletes SOC but also has adverse effects on other soil physical and chemical properties (Balesdent et al., 2000; Blanco-Canqui and Lal, 2009; Blanco-Canqui et al., 2006b; Moebius-Clune et al., 2008). The 21% decrease in SOC during P1 could adversely affect soil aggregate stability and soil structure (Blanco-Canqui and Lal, 2009), and reduce the soil water holding capacity (Gollany et al., 1992; Lal, 2007; Mann et al., 2002). Karlen et al. (1984) concluded that harvesting crop residue from this site for 2 yr significantly reduced the K concentration in the topsoil and increased the annual N, P, and K removal.

Mitigation of Residue Harvest Impact on Soil Organic Carbon Stocks

The potential impacts of 50 and 90% residue removal on SOC stocks while changing management from the DT to the CS system in 1995 were simulated to examine the mitigation potential of less intensive tillage (Fig. 6). Simulated SOC stocks in the 0- to 5- and 5- to 10-cm depths decreased from 1996 to 1999, then started to increase with conversion from DT to CS and 50% residue harvest. During the 19 yr of CS tillage and 50% residue harvest, SOC stocks increased by 3.0 g SOC kg^{-1} (32%) in the 0- to 5-cm depth and 1.3 g SOC kg^{-1} (1%) in the 10- to 15-cm depth with conversion to CS (Fig. 6b). Simulated SOC stocks decreased only in the 5- to 10-cm depth, while SOC stocks were maintained in the 0- to 5- and 10- to 15-cm depths after 19 yr of 90% residue harvest and conversion to CS (Fig. 6c). The CQESTR model predicted SOC stocks to decline by 9% in the 5- to 10-cm soil depth with 90% residue removal under CS. The simulation results suggest that CS can mitigate the loss of crop residue C with moderate residue harvest; however, the direct impact of residue harvest remains to be evaluated under field conditions.

Potential Effects of Residue Harvest on Soil Organic Carbon Stocks under Established Conservation Tillage

After 23 yr of 66% residue harvest, CQESTR predicted a decrease in SOC stocks of 30% in the top 5-cm soil depth (Fig. 7; Table 5). This reduction is about 9% greater than under DT (30 vs. 21%). In terms of SOC lost, however, the loss is twice as great under CS (4.5 g SOC kg^{-1}), compared with only 1.9 g SOC kg^{-1} under DT. Maintaining SOC stocks under a CS system with a higher SOC level requires higher OM input than under DT. The greater SOC loss under CS than DT may be attributed to a higher microbial population under the CS system. Liebig et al. (2004) reported a twofold increase in microbial biomass C within the surface 7.5 cm under NT compared with a conventional tillage system. The predicted SOC stocks declined by 1.5 g SOC kg^{-1} in the 5- to 10-cm soil depth under the P1-H66 residue harvest scenario (Table 5). An 18% reduction in SOC stocks at 5 to 10 cm was similar to that under DT for the same scenario. The predicted declines of SOC stocks under the P2-H50 scenario, however, were 8 and 5% in the 0- to 5- and 5- to 10-cm soil depths, respectively (Fig. 8; Table 5).

Following 90% residue harvest, CQESTR predicted decreases in SOC stocks of 41 and 28% in the 0- to 5- and 5- to 10-cm depths, respectively (Fig. 7). The predicted loss of 6.1 g SOC kg^{-1} at the 0- to 5-cm depth is 70% of the amount of SOC gained (8.9 g SOC kg^{-1}) after implementing the new tillage practice (i.e., CS) since 1979. After 19 yr of 90% biomass harvest under the P2-H90 scenario, SOC stocks decreased by 23 and 11% in the 0- to 5- and 5- to 10-cm soil depths, respectively (Fig. 8), which was less severe than under P1-H90. This drastic residue removal (P1-H90) for 23 yr could adversely affect soil physical, chemical, and biological properties (Blanco-Canqui and Lal, 2009; Larson, 1979; Powlson et al., 2008). Blanco-Canqui and Lal (2009) reported that complete stover removal for 4 yr reduced total N by, on average, 0.82 Mg ha^{-1} in the 0- to 10-cm depth of a silt loam soil but had no effect in a clay loam soil. They also reported that Ca^{+2} and Mg^{+2} and the cation exchange capacity were reduced by 10% with >75% stover removal. Available P and exchangeable K^{+} were reduced by 40 and 15%, respectively (Blanco-Canqui and Lal, 2009).

Maintaining SOC is a vital factor for sustaining soil functions and properties. Fronning et al. (2008) suggested the use of C amendments such as manure, compost, or cover crops to maintain or increase SOC levels by replacing the C removed with the maize stover. A decrease in SOC can reduce nutrient availability and consequently reduce crop yield if supplemental fertilizer is not added to replace nutrients lost with residue removal (Blanco-Canqui and Lal, 2009; Larson, 1979; Wilhelm et al., 2004). Declines in SOC stocks in this inherently low-SOC loamy sand soil (Hunt et al., 1996) could adversely affect its soil physical, chemical, and biological properties and its production capacity.

Implication of Residue Harvest and Tillage Effects for Atmospheric Carbon Dioxide Mitigation Potential

Predicted declines in SOC with similar amounts of residue harvest were more severe under CS than under DT. This may be attributed to shifts in the relative amounts of labile and more recalcitrant forms of SOC, or changes in soil respiration rates due to greater microbial biomass oxidizing the increased amount of available substrate. Significantly higher microbial biomass, particulate organic matter, and potentially mineralizable N under less intensive tillage compared with conventional tillage were reported by Liebig et al. (2004). Under the DT system, it is likely that there was more recalcitrant or relic SOC resulting in lower C loss rates. Alternatively in the CS system, with greater and more recent OM accretion, a greater fraction of SOM is expected to be more labile, resulting in higher C loss rates than under DT. Maize residue contains about 29% soluble organic compounds, 55% hemicelluloses and cellulose, 10% N, and only 6% lignin (Buyanovsky et al., 1997). The maize biomass might have contributed to a labile pool of SOM under CS, resulting in a fast mineralization rate and short half-life. The predicted loss of 6.1 g SOC kg^{-1} (41%) in the top 5 cm for the CS system with 90% residue harvest not only impacts the soil health and production capacity but will reduce the net mitigation potential of the soil to decrease atmospheric CO_2. Overall potential changes in productivity and C sequestration for the entire field might be negligible, but as in any managed ecosystem, soil health and nutrient management in industrial biomass agriculture must address multiple criteria, including air and water quality, nutrient use efficiency, and farm economics (Anex et al., 2007).

SUMMARY AND CONCLUSIONS

The CQESTR model allowed successful evaluation of the potential long-term effects of changes in management, such as stover harvest and tillage practices, from a loamy sand southeastern Coastal Plain soil, providing insights that were too costly to be obtained by field measurements. The CQESTR model captured temporal changes in SOC. The simulated SOC stock gain was more than threefold greater under CS than DT. After 23 yr of 66% residue harvest, CQESTR predicted 21 and 30% reductions in SOC stocks for the 0- to 5-cm depth under DT and CS systems, respectively, compared with no residue harvest. Crop residue harvest under CS at low initial SOC contents induced severe SOC losses, especially in the top 5-cm depth, in comparison with H0; however, the predicted SOC stocks under CS were about 5 g SOC kg^{-1} greater than under DT, even with 90% residue harvest. The CS system, with a higher labile fraction than a passive or relic SOC form, resulted in higher C loss rates than under DT. While CS can somewhat mitigate the loss of soil C, a high rate of residue harvest may have an adverse impact on SOC stocks. The loss of SOC could reduce nutrient availability and consequently reduce the production capacity of this inherently low-SOC loamy sand soil.

This simulation shows that conservation tillage is an investment in future resource alternatives in South Carolina coastal soils. Nonetheless, even under CS, a high residue harvest rate from soils with this type of parent material will probably have an adverse impact on the SOC content. This, in turn, will have adverse implications for soil and water resources. Large-scale residue harvest for bioenergy must be balanced with other critical functions that agricultural lands provide, including nutrient and water cycling and C sequestration, for the maintenance of soil productivity. The quantity of crop residue that can be sustainably harvested is directly influenced by several factors, including the initial SOC stocks (i.e., the SOC status of the soil) of a particular soil, climate, crop yield, crop rotation, field management practice (e.g., the type and timing of tillage and other management practices), and the physical characteristics of the soil (soil type, slope, erodibility index, topography, etc.). More long-term field data are required to validate the predicted SOC stocks under a wide range of soils, climatic conditions, and management practices including crop residue harvest scenarios. Information is also needed on the potential for C storage below the surface 30 cm, and the effects of interactions of crop rotations and cover crops on SOC and net CO_2 emissions. We will then be able to make more effective decisions as we balance competing priorities with regard to (i) advances in energy conversion technology, (ii) the need for C sequestration, (iii) the necessity of sustaining soil and water resources, and (iv) the production of food and fiber.

ACKNOWLEDGMENTS

This manuscript is dedicated to the memory of Dr. Wallace W. Wilhelm. We thank Dr. C. Walthall for his support of the modeling effort, and Dr. M.A. Liebig for helpful comments. Technical assistance and data collection by Mr. Don Watts is gratefully acknowledged. This publication is based on work supported by the USDA-ARS under the GRACEnet and REAP projects.

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